Improved atmospheric stable boundary layer formulations for Navy Seasonal Forecasting

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LONG-TERM GOALS

To develop methods, descriptions and parameterizations that will alleviate long-standing problems in basically all large-scale numerical atmospheric models in dealing with statically stable and/or very stable conditions, and to implement these for Navy extended forecasting.

OBJECTIVES

Many large-scale weather forecast models prescribes too much turbulent mixing stably stratified conditions, which causes problems with the depth of nocturnal or high-latitude winter boundary layers, lack of inertially driven low-level wind maxima and inversion-capped low clouds. The link between the turbulent momentum flux and the associated Ekman pumping and therefore the lifetime of synoptic-scale weather system has so far made impossible a satisfactory solution.

Several detrimental feedbacks are also involved in this problem. For example, while there is a negative balancing feedback between stability and the sensible heat flux in the unstable boundary layer (larger instability → more heat flux → less instability etc.) and the momentum flux at larger instabilities becomes more or less unimportant, this feedback works the other way for stable stratification: larger stability → less heat flux → even larger stability etc., until balanced by mixing generated by wind shear the momentum flux. The balance between the buoyancy destruction and wind-shear generation of turbulence thus becomes critical to prevent for example model surface temperature to plunge. For the latter reason, the momentum generation is typically exaggerated to be on the safe side; this, however, have the detrimental effects discussed above.

The objectives of this project are to develop and understanding in three specific areas and to explore if these concepts can be used to alleviate the problem described above. These specific areas are:

1. The “Total Turbulent Energy” (TTE) approach, in which turbulent potential energy is included in a new prognostic variable, which allows kinetic energy to be transformed into potential energy for later retransformation, and not be dissipated for ever.

2. Turbulence generation by breaking of small-scale sub-grid topography-generated gravity waves, which may happen in the boundary layer even at seemingly modest terrain variations, due to its inherent-wind turning and thus potential formation of a critical layer.

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3. Uncertainty in turbulence flux-gradient relationships, by exploring probabilistic expressions for these.

APPROACH

All model implementations will be explored either in a regional model setting, using COAMPS, or in a single column version of the NOGAPS/NAVGEM model, before being implemented in a global context. Both the single-column and global modeling concepts can be either directly implemented in Navy models provided we can have simple access to these, or in the ECMWF version of the Integrated Forecasting System (IFS) to which we have access through the OpenIFS project. All steps of the development and testing will involve evaluations of model results against filed observations to ensure the correct results for the correct reasons. As test beds we will start using data from the SHEBA and CASES99 experiments. The former has long periods of stable stratification during the Arctic winter while the latter is dominated by nocturnally stable conditions. These two types differ in that while the latter involves a capping near-neutral residual layer, the Arctic case develops a strong and continuous stratification through the whole troposphere; buoyancy waves can travel very far in that environment and still affect the surface.

For the TTS implementation, this has been achived already in WRF and will now be attempted in COAMPS. The TTE will be embedded in an EDMF context and in contrast to WRF we will use couple the formulation for the stably stratified case (the ED part) to a probabilistic mass flux model also developed and used in this project, by Dr Joao Teixeira's group.

For the work on gravity wave breaking we are collaborating with Dr Carmen Nappo who has developed a saturation-critical layer analytic model that takes a terrain data base and wind speed and direction profiles to solve for the momentum deposition necessary to prevent waves from breaking; this is necessary to stay in the linear model concept but the energy deposited should be the same as that would be generated by the breaking waves. This analytic model, that scans for possible propagation directions to find a critical layer will be coupled first to a single column model, then to COAMPS and eventually to a global model.

For the description of uncertainty in the flux-gradient relationship, we collaborate with Dr Larry Mahrt who has significant amounts of data from stable conditions in various settings. Together we will generate a pdf-based relationship between the flux of momentum and the wind speed gradient; for each stability, there will thus be a pdf of such relationships and in the model we will sample that pdf such that over time the ensemble average relationship will be conserved. Since the pdf is very likely skewed, we expect that this will allow a reduction in mean mixing while maintaining the stratification thus alleviating some of the basic problems described above.

WORK COMPLETED

The first thing that has to happen with a program of this kind after it is funded is hiring of staff. This is an ongoing task; the post-doc funded under this Grant was during the previous winter and started working in April 2012. A PhD student that will also work with this project starts 1 January 2013.

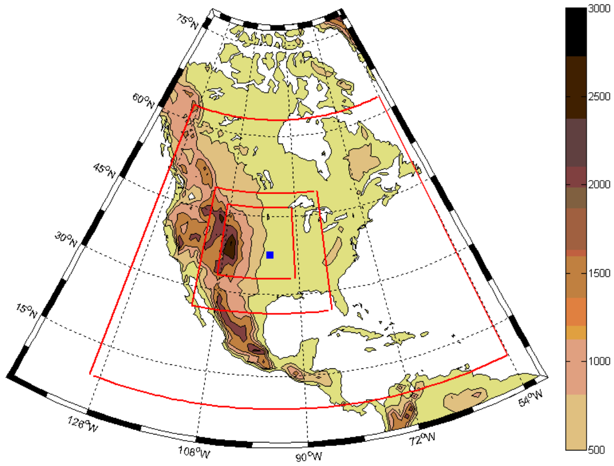

Figure 1 The domain(s) of COAMPS used here showing the outer (parent) domain at 54 km resolution and the two nests at 18 and 6 km resolution, repectively.

As a first start of the program, COAMPS was set up for the CASE99 field project area and some preliminary runs completed.

The intention here is to first run COAMPS for the entire CASE99 period to facilitate a more statistical evaluation, even though case studies will also be considered. Figure 1 shows the model domain and Figure 2 illustrates some of the first results, comparing COAMPS wind speed and temperature profiles against a select set of sounding profiles from the field deployment.

Work will continue on this evaluation, and in parallel the work on the research topics will be developed so that once we have schemes ready for testing, the will be implemented in COAMPS and the whole CASES99 period re-run; this will facilitate an immediate measure of the improvements and will help guide further refinements of the new schemes so that testing in a global setting can be keept at a reasonable level.

Some preliminary tests with a simple version of the probabilistic momentum flux formulation was implemented and tested in a single-column model, however, not for any of the Navy models, since a single-column version of NOGAPS or NAVGEMS still does not exist. The results of this very “quick-and-dirty” implementation are quite promising (Figure 3).

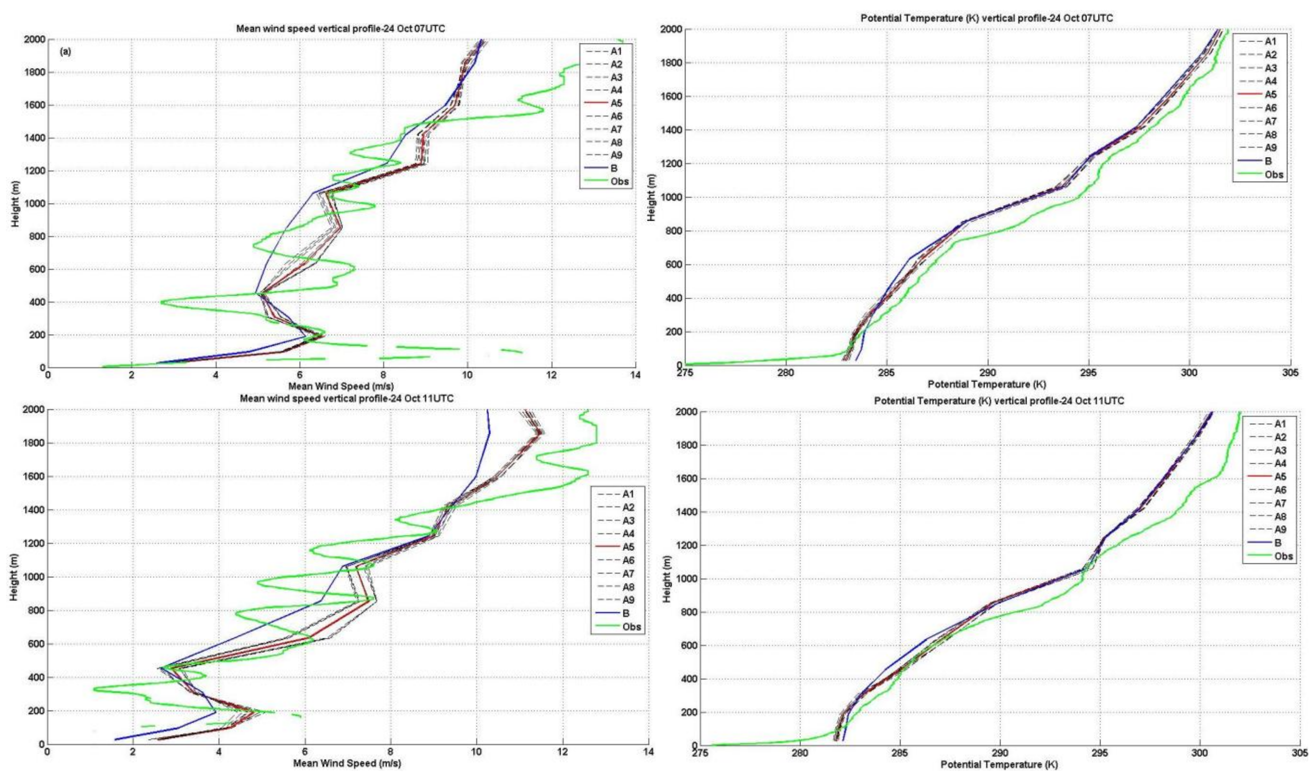

Figure 2. Examples of COAMPS comparison to two soundings for one particular night, 24 October, during CASES99. Left two panels show the wind speed and right two panels shows the potential temperature; green line is soundings (when dashed some data is missing) and all other lines are from the model; the blue solid line is from the parent fomain at the location marked in Figure 1 and the red solid line is from the same geographical point but from the inner nest, while dashed black lines are also from the innermost nest but from grid points surrounding.

RESULTS

In general, COAMPS compares reasonably well to soundings from CASES99, recalling that the soundings are a "snap-shot" of the conditions while the model represents a time-and-space average and is expected to have much less variability.

Figure 2 shows some of the preliminary results; biases in temperature are quite small, but the stability near the surface in the observations is much larger than in the model; thus the surface temperature differences can easily be O(10K) while the typical temperature bias in the bulk of the profile is O(1K). The general character of the temperature profile is increasingly near neutral while approaching the surface, while this is true in the observations only down to 100 – 200 m; below this the temperature gradient sharpens again. Conditions during daytime (not shown) are in a sense the opposite; the bias in the profile is somewhat larger while the simulated near-surface temperature is closer to the observations.

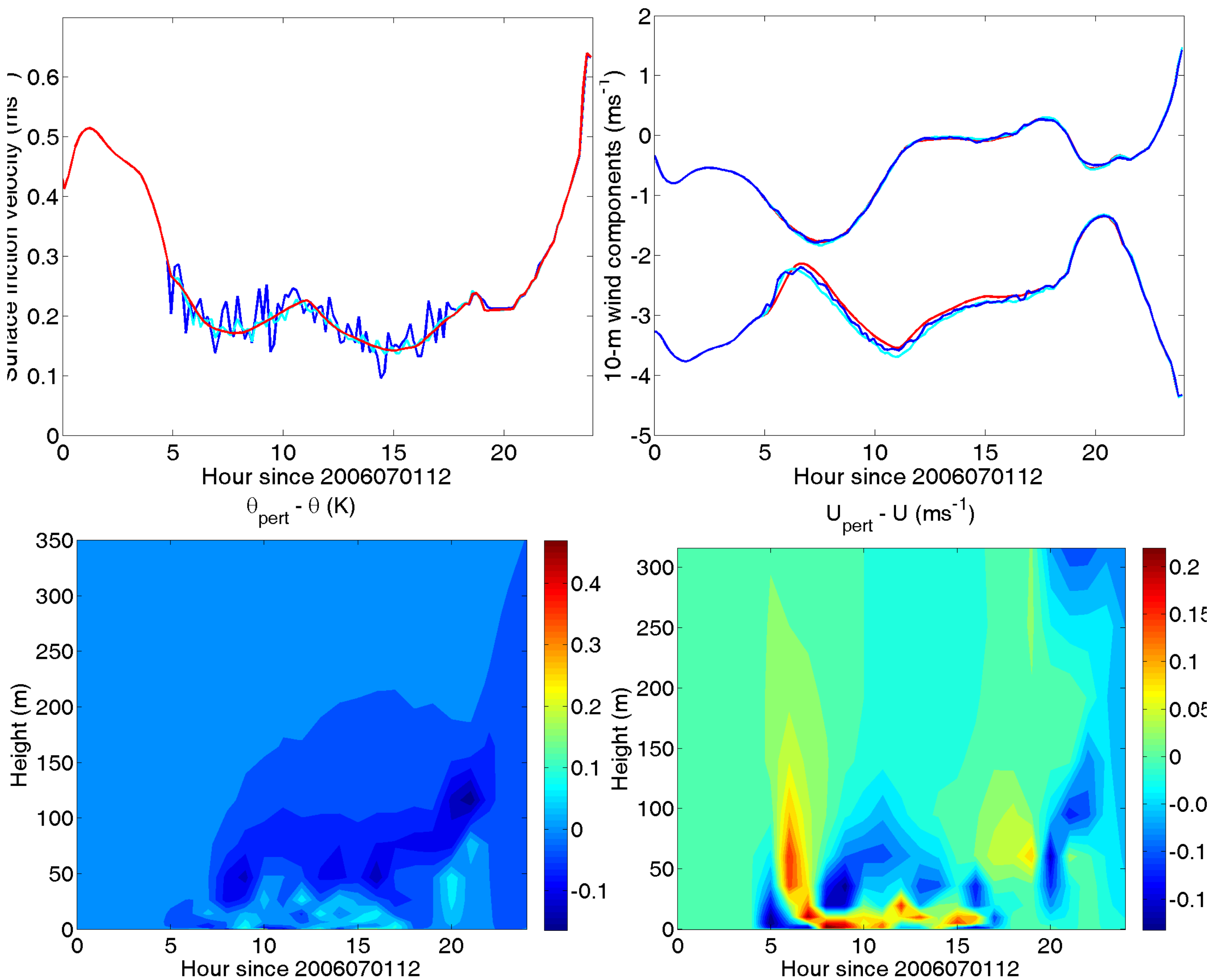

Figure 3. Some preliminary results from (top left) randomly perturbing the friction velocity in a model up or down by 50% over different time scales and (top right) the resulting 10-meter wind speeds. The lower panels show the difference between the simulation with a long time-scale perturbation and one without any perturbations at all for (lower left) potential temperature and (lower right) scalar wind speed.

The observed wind-speed profiles are more variable which complicates the evaluations; this is a consequence of the soundings being a single snap-shot of the profile. Moreover, the GPS sensor on the sonde was less effect closer to the surface and therefore there are some data dropouts. In general the results for the high-resolution nest are closer to the observations, as expected but the extreme wind, especially in the forming low-level jet the simulations underestimate the winds significantly, by 2 - 5 ms^{-1}, also indicative of excess mixing.

For the stochastically varying friction velocity, we used a single column model and just calculated a randomly varying number between 0.5 and 1; this value was set constant for differently long time periods, 20 seconds and 200 seconds, and was then used to multiply the friction velocity calculated in the model.

Figure 3 shows the effects on the friction velocity itself (top left) and for the 10-m wind speed, indicating that the "average" friction velocity remains unchanged and that also the impact on the 10-m wind speed components is quite small. Interestingly, in the two bottom panels there is a systematic change in the vertical distribution of both temperature and wind speed, so that even though the change in the actual values are small the gradients are affected quite a lot. Both the temperature and momentum is more well mixed (smaller gradients) but since the Richardson number involves the wind-speed gradient squared, it is reasonable to assume that the Richardson number (***Ri***) is increased.

The end result of this simple exercise is thus that the boundary-layer becomes more well mixed at a higher ***Ri***, implying that the mixing could in fact be relaxed (smaller diffusivity) while retaining a high, or even higher, ***Ri***. This work needs to be refined and most likely we will perturb the mixing length to make the perturbation consistent through the vertical. This will entail first finding out a vertical decorrelation length; later when implemented in a 3D model we will also need a horizontal decorrelation length.

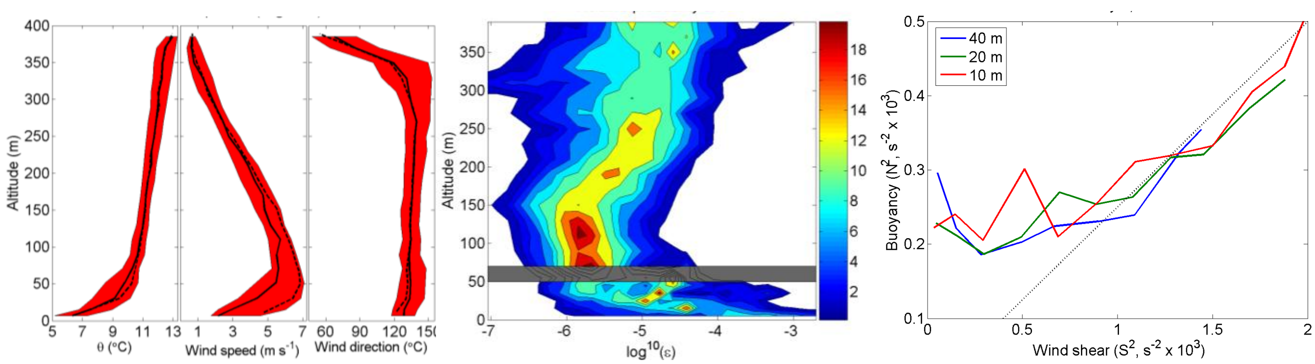

Figure 4. Example of wave breaking from observations from CASES99; (left) mean profiles of temperature, wind speed and direction, (middle) probability of TKE-dissipation rate and (right) buoyancy against winds shear frequency for different averaging depths (colored lines, the thin black line indicates ***Ri*** = 0.25)

Finally, Figure 4 illustrate the effect of breaking gravity waves on the turbulent kinetic energy (TKE, using its dissipation rate as a proxy, see middle panel). The right panel shows how ***Ri*** approaches 0.25, a commonly used value for its critical value. This we interpret so that as the wave amplitude increases, the energy of the wave is transferred to TKE preventing the wave from breaking, as is assumed in the wave saturation theory. The wave is generated by very modest terrain; by all eye witness accounts the terrain at the CASES99 is quite flat. The reason the gravity waves break is the critical layer that is formed as the wind direction turns into the propagation direction of the waves. We are now working on a model that will deal with this in a single-column setting however, for a proper implementation we

need a 3D model to be able to simulate the wind direction turning away from the surface and the stabilization of the residual layer; both this needs 3D effects.

IMPACT/APPLICATIONS

A better treatment of the stanle boundary layer processes is directly directed towards reducing some persistent systematic errors in several the near-surface variable while maintaining the forecast quality on the synoptic scales by not ad´veresely affecting the Ekman pumping in the boundary layer.